VTT Technical Research Centre of Finland

Empowering and engaging industrial workers with Operator 4.0 solutions

Kaasinen, Eija; Schmalfuß, Franziska; Özturk, Cemalettin; Aromaa, Susanna; Boubekeur, Menouer; Heilala, Juhani; Heikkilä, Päivi; Kuula, Timo; Liinasuo, Marja; Mach, Sebastian; Mehta, Rakesh; Petäjä, Esko; Walter, Thomas

Published in:
Computers and Industrial Engineering

DOI:
10.1016/j.cie.2019.01.052

Published: 01/01/2020

Document Version
Publisher's final version

Computers & Industrial Engineering 139 (2020) 105678

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Empowering and engaging industrial workers with Operator 4.0 solutions

Eija Kaasinen[a,*], Franziska Schmalfuß[b], Cemalettin Özturk[c], Susanna Aromaa[a], Menouer Boubekeur[c], Juhani Heilala[a], Päivi Heikkilä[a], Timo Kuula[a], Marja Liinasuo[a], Sebastian Mach[b], Rakesh Mehta[c], Esko Petäjä[d], Thomas Walter[e]

[a] VTT Technical Research Centre of Finland Ltd, Visiokatu 4, FI-33101 Tampere, Finland
[b] Chemnitz University of Technology, Straße der Nationen 62, 09111 Chemnitz, Germany
[c] United Technologies Research Centre Ireland, Penrose Wharf, Cork, Ireland
[d] Finn-Power Oy, P.O. Box 900, 60101 Seinäjoki, Finland
[e] Continental Automotive GmbH, Ostring 7, 09212 Limbach-Oberfrohna, Germany

ARTICLE INFO

Keywords:
Adaptation
Worker model
Empowerment
Engagement
Factory automation
Training
Knowledge sharing
Participatory design
User studies
Factory work

ABSTRACT

Industry 4.0 has potential for qualitative enrichment of factory work: a more interesting working environment, greater autonomy and opportunities for self-development. A central element of Industry 4.0 is human-centricity, described as development towards Operator 4.0. Our Operator 4.0 vision includes smart factories of the future that are perfectly suited for workers with different skills, capabilities and preferences. The vision is achieved by solutions that empower the workers and engage the work community. Empowering the worker is based on adapting the factory shop floor to the skills, capabilities and needs of the worker and supporting the worker to understand and to develop his/her competence. Engaging the work community is based on tools, with which the workers can participate in designing their work and training, and share their knowledge with each other. We gathered requirements from three manufacturing companies in different industries and interviewed 44 workers in four factories in order to study their expectations and concerns related to the proposed Operator 4.0 solutions. Adaptation was considered useful both in manufacturing systems and in production planning. However, worker measuring and modelling raised many doubts within workers and also with factory management. Therefore it is important to provide early demonstrations of the ideas and to design them further with the workers in order to find acceptable and ethically sustainable ways for worker modelling. The workers would like to be more involved in the design of the work place and manufacturing processes, and they thought that participation would decrease many problems that they currently face in their work. However, there were also doubts concerning whether they really could have possibilities to impact on their work. The results show that there are clear needs for knowledge sharing and adaptive learning solutions that would support personalized competence development and learning while working. An easily accessible platform for knowledge sharing could evolve to a forum where good work practices and ways to solve problems are shared not only within the work community, but also with machine providers and other stakeholders. The interviewees saw the virtual factory as a promising platform for participatory design and training.

1. Introduction

The fourth industrial revolution, often referred to as Industry 4.0, is already on its way. Enabled by advanced digitalization, industrial internet and smart technologies such as Internet of Things (IoT), it is expected that Industry 4.0 will result e.g. in shorter development periods, individualization in demand for the customers, flexibility, decentralization and resource efficiency (Lasi, Fettke, Kemper, Feld & Hoffmann, 2014; MacDougall, 2014). Industrial internet and IoT have been widely studied from the viewpoints of management, business and technology. They are also expected to change radically many work roles, but this has been studied less. In the industry, there will be significantly greater demands on all members of the work force, in terms of managing complexity, abstraction and problem-solving (Kagermann,

* Corresponding author.
E-mail addresses: Eija.Kaasinen@vtt.fi (E. Kaasinen), Franziska.Schmalfu@psychologie.tu-chemnitz.de (F. Schmalfuß), OzturkC@utrc.utc.com (C. Özturk), Susanna.Aromaa@vtt.fi (S. Aromaa), boubeKM@utrc.utc.com (M. Boubekeur), Juhani.Heilala@vtt.fi (J. Heilala), Paivi.Heikkila@vtt.fi (P. Heikkilä), Timo.Kuula@vtt.fi (T. Kuula), Marja.Liinasuo@vtt.fi (M. Liinasuo), Sebastian.Mach@psychologie.tu-chemnitz.de (S. Mach), MehtaR1@utrc.utc.com (R. Mehta), esko.petaja@primapower.com (E. Petäjä), thomas.2.walter@continental-corporation.com (T. Walter).

https://doi.org/10.1016/j.cie.2019.01.052

Available online 30 January 2019

Wahlster, & Helbig, 2013). For the industrial workers, the revolution is expected to provide opportunities by the qualitative enrichment of their work: a more interesting working environment, greater autonomy and opportunities for self-development (MacDougall, 2014). Subsequently, the employees are likely to act much more on their own initiative, to possess excellent communication skills and to organize their personal workflow; i.e. in future industrial environments, they are expected to act as strategic decision-makers and flexible problem-solvers (ElMaraghy, 2005; Gorecky, Schmitt, Loskyll & Zühlke, 2014).

Today's manufacturing environment is highly uncertain and dynamic. It is characterized by shorter life cycles of products and technologies, shorter delivery times, increased levels of customization at the price of standard products, increased product variety, quality as well as demand variability, and intense global competition (Jain, Jain, Chan, & Singh, 2013). The changing requirements call for adaptive and rapidly responding production systems that can adjust to the required changes in processing functions, production capacity and the distribution of the orders (Järvenpää, 2012).

A central component of Industry 4.0 is its human-centricity, described as development towards the Operator 4.0 concept (Romero, Bernus, Noran, Stahre, & Fast-Berglund, 2016). Operator 4.0 refers to smart and skilled operators of the future, who will be assisted by automated systems providing a sustainable relief of physical and mental stress and allowing the operators to utilize and develop their creative, innovative and improvisational skills, without compromising production objectives (Romero, Bernus et al., 2016). Romero, Stahre, et al. (2016) postulated an Operator 4.0 typology and argued that one operator could incorporate one or several of the proposed types. The authors differentiated between the Super-strength Operator (e.g., using Exoskeletons), the Augmented Operator (e.g., using augmented reality tools), the Virtual Operator (e.g., using a virtual factory), the Healthy Operator (e.g. using wearable devices to track well-being), the Smarter Operator (e.g., using agent or artificial intelligence for planning activities), the Collaborative Operator (e.g., interacting with CoBots), the Social Operator (e.g., sharing knowledge using a social network) and the Analytical Operator (e.g., using Big Data analytics).

Gorecky et al. (2014) as well as Romero, Bernus et al. (2016) described factory operators integrated into the cyber-physical world so that their individual skills can be utilized. Optimal integration of physical and virtual reality was also pointed out by Longo, Nicoletti, and Padovano (2017), who proposed Augmented Reality (AR) content and a personal digital assistant for smart factory operators, as was also described by Romero, Stahre, et al. (2016). Operator 4.0 factory work will be qualitatively enriched and flexible, and will require new qualifications to master the digital technology invading factories. Future factories should support current workers in learning new skills while tempting new workers who are already familiar with digital solutions. The Operator 4.0 paradigm shift cannot succeed just by introducing new technologies to the factory floor. Work processes need to be reshaped and new approaches to training are needed in order to support continuous development of skills.

In our Factory2Fit research project (www.factory2fit.eu), started late in 2016, we aim to take human-centered manufacturing to a new level by giving the factory workers a leading role in adapting and developing their own job. The Factory2Fit solutions will support our Operator 4.0 vision of smart factories of the future that will be perfectly suited for workers with different skills, capabilities and preferences. The objective of the project is to develop and pilot solutions that empower the workers and engage the work community (Fig. 1). Overall, our approach addresses almost all the different types of Operator 4.0 (Romero, Stahre, et al., 2016), except for the Super-Strength Collaborative Operator.

Empowerment is supported by adaptive human-automation interaction solutions that improve the flow of working and support the worker in understanding and developing his/her competences. The main principle is that the worker is an expert of his/her own job and thus s/he should have an active role in the adaptation. A dynamic user model is maintained based on measuring and monitoring the worker and the manufacturing environment. The adaptation solutions utilize the user model to change the automation level and other system features accordingly. Measuring and monitoring of the user is based on the quantified worker approach (Heikkilä, Honka, & Kaasinen, 2018): the measures and monitoring are not only used by the automation system to adapt but the worker him/herself also gets empowering feedback of his/her competence and performance. This supports the worker in the continuous development of his/her competences and the feedback is also utilized in adaptive learning solutions at work.

The work community is *engaged* to share knowledge and to participate in designing the work processes and training. To that end, a virtual model of the factory will be created, representing all essential functionalities of the real factory. The virtual factory model will then be used as a platform for engaging the work community in participatory design activities. The model supports seeing one's own job, other worker's jobs and their roles in the overall context of the manufacturing process. The virtual factory model also acts as a motivating and easy-to-use contextual platform for knowledge sharing with social media-based tools for sharing e.g. good practices, notices and observations. Furthermore, the virtual factory model serves as a platform for contextual training.

In this paper we analyse user expectations and concerns related to the proposed Operator 4.0 concepts based on interviews and observations of factory workers in four pilot factories. Accordingly, we present design implications for empowering and engaging Operator 4.0 solutions.

The paper is structured in the following way: In Section 2, we describe related research on our core development themes: work well-being, empowering the worker and engaging the work community. In Section 3, we describe the three industrial pilot environments and the industrial expectations of Continental, Prima Power and United Technologies Corporation (UTC). In Section 4, we describe the methods and results of the user studies that we carried out at the four factories. Finally, in Section 5, we conclude the results into design implications, and in Section 6, we discuss the results and compare them with earlier studies. In Section 7, we describe our future plans.

2. Related research

In the following, we provide an overview of earlier research related to our Operator 4.0 concept. This concept aims to increase work well-being by empowering the worker and engaging the work community. We first present an overview of research related to work well-being. Regarding empowerment, we describe how factory environments have been adopted to the workers in earlier research. Regarding engagement, we describe earlier research related to participatory design, knowledge sharing and training.

2.1. Work well-being

Work environments should be designed both for productivity and work well-being, as these factors are interconnected (Edwards & Jensen, 2014). According to Schaufeli and Bakker (2010), work well-being consists of job satisfaction and work engagement. Job satisfaction can be defined as: "a pleasurable or positive emotional state resulting from the appraisal of one's job or job experiences" (Locke, 1976), or "the extent to which people like (satisfaction) or dislike (dissatisfaction) their jobs" (Spector, 1997). The extent to which work properties meet or exceed the personal expectations of employees determines the level of job satisfaction (Locke, 1976). Satisfaction with the nature of work, including job challenge, autonomy, variety and scope, best predicts overall job satisfaction (Saari & Judge, 2004). Maslach and Leiter (1997) defined work engagement as referring to energy, involvement and professional efficacy. According to Schaufeli, Salavona, González-

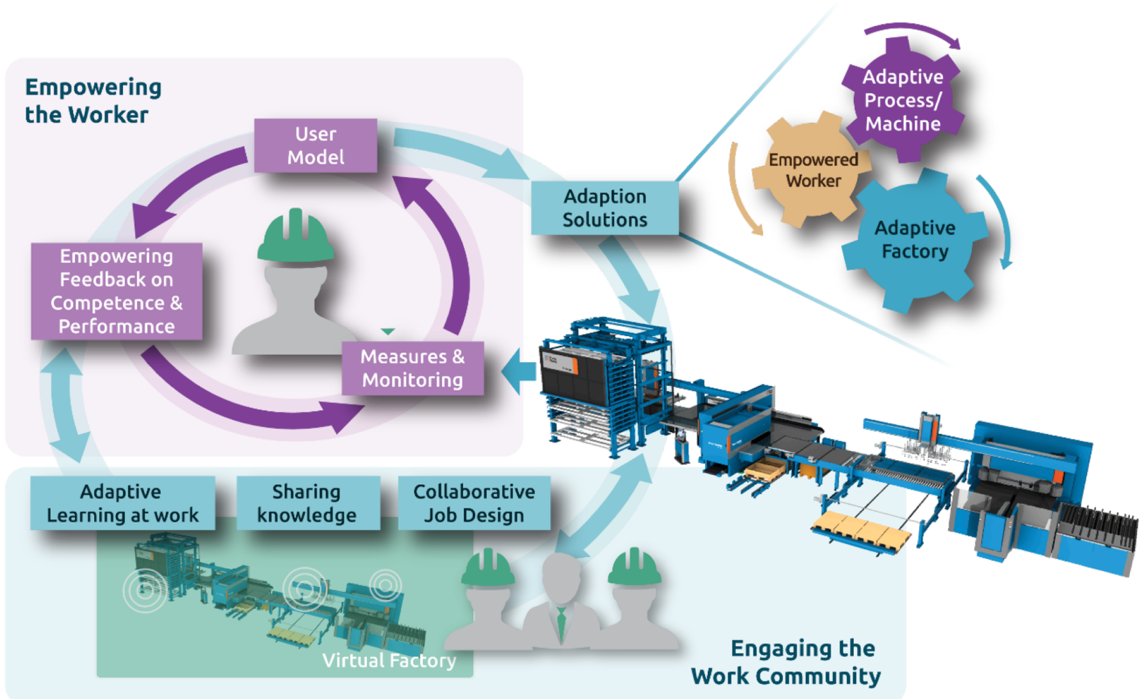

Fig. 1. Our Operator 4.0 vision based on empowering the worker and engaging the work community.

Romá and Bakker (2002), work engagement is "a positive, fulfilling, work-related state of mind that is characterized by vigor, dedication and absorption" (p. 74).

Over the past decades, advances in personal health technologies have enabled new ways of monitoring human behaviour. Today, personal monitoring devices and applications such as wearable motion trackers, heart rate monitors and health-related mobile applications are easily accessible consumer products. Employees could also benefit from the use of personal health technologies to get empowering feedback of their well-being in relation to different jobs. However, significant numbers of employees are not interested in adopting the technologies currently available, or their use declines after some initial enthusiasm (Mattila et al., 2013).

2.2. *Empowering the worker by adaptation of the factory environment*

Smart factories have been defined as a manufacturing solution that provides such flexible and adaptive production processes that will solve problems arising in a production facility with dynamic and rapidly changing conditions in a world of increasing complexity (Radziwon, Bilberg, Bogers, & Madsen, 2014). By definition, "smart" factories should be designed to increase factory productivity as well as efficiency.

Flexibility is often referred to as the ability to adapt to different requirements without physical changes to the system, whereas re-configurability refers to the ability to change system components when new requirements arise (ElMaraghy, 2005). In the manufacturing domain there is a need for flexibility, i.e. adaptation to external forces such as product and production volume changes, technology changes or customer orders.

Human operators are key resources in smart manufacturing. In the past, the human operator had to adapt to processes and systems, the key drivers being efficiency, productivity and cost savings. Emerging digital technologies make machines and processes so automated that these performance measures are already guaranteed. However, exploiting the flexibility and creativity of human workers is becoming more important to gain a competitive advantage in today's business. Henceforth, the paradigm is shifting to fit systems to the human operator, and work satisfaction is a key issue. Adaptation according to the human operator has been developed from different viewpoints: adaptation to human physics with work ergonomics (Heilala & Voho, 1997), adaptation to human skills (Heilala & Voho, 1997), adaptation of interaction (Rothrock, Koubek, Fuchs, Haas, & Salvendy, 2002) and adaptation of the Level of Automation (LoA) (Johansson et al., 2009). Chen, Huang, Chou, Shih, and Liu (2012) presented a model-based approach for developing configurable user centric automation and assistive devices. Zhou, Zhang, Liu and Xing (2011) pointed out that existing user modelling approaches are very dependent on users' explicit feedback to adapt to the drift of user preferences over time.

One of the key components of adaptive production is resource scheduling (Leung, 2004). Scheduling refers to the organization of production with different available machines, hundreds or even thousands of employees, whose efforts should be coordinated towards reaching common goals. The end result of the scheduling process is a plan, the quality of which can be measured by (a) flexibility and adaptability; (b) timely delivery of orders; (c) resource utilization; (d) timely response to unexpected events; (e) minimum downtime; and (f) isolation and elimination of production bottlenecks (Leung, 2004). Adaptation can focus on scheduling and work management (Spilevoy et al., 2013; Goryachev et al., 2013). Worker preference-based task assignment and scheduling algorithms support the adaptability of the scheduling process (Jaturanonda & Nanthavanij, 2011; Colucci et al., 2004).

2.3. *Engaging the work community by participatory design, knowledge sharing and training*

In order to engage the work community to see the factory as a wider entity than just their own job, *virtual factory models* provide a promising platform. The utilization of simulation and visualization packages in the factory domain, particularly in manufacturing and processing, has been increasing exponentially during the past five decades in parallel with the development of the ICT technologies which have enhanced the visualization and data management with the new generations of simulation engines and 3D visualization engines (Mourtzis & Doukas, 2014).

Table 1
Overview of the industrial pilot environments.

	Prima Power	Continental	UTC
Pilot sites	Customer A and B, who use Prima Power's multifunctional sheet metal working machinery	Continental's mass production line	Air Handling Unit assembly workshop of Carrier, a unit of UTC Corporation
Products	Customized sheet metal parts	Injectors for diesel engines	Air handling units
Automation level	High	High	Low
Worker main tasks	To keep the machinery running according to the production plan	To keep the process under control and in stable condition	Completing assembly orders at the station
Expectations for the project	Smooth user experience for the operators Fast recovery from error situations Quicker learning curve for customers	Increase the controllability and usability of the processes Better work results Less production interruptions Faster recovery from disturbances	Increased performance Increased work satisfaction

The utilization of virtual factory models requires a simulation environment that faithfully reflects reality. The utilization of simulation for a virtual factory model brings a large number of proved advantages such as deeper understanding of the whole factory, and reduces commissioning ramp-up times and testing of proposed changes (Turner, Hutabarat, Oyekan, & Tiwari, 2016). Novak-Marcincin, Barna, Janak, and Novakova-Marcincinova (2013) discussed the possibility of using various virtual tools in manufacturing processes.

The *participatory design (PD)* approach involves users to contribute to a design process (Ehn, 1993; Muller & Kuhn, 1993). In participatory design, benefits come from sharing knowledge between designers and users as well as other stakeholders, and learning from each other. The interaction between individuals supports the sharing of often more or less hidden (tacit) knowledge (Nonaka, 1994). Tacit knowledge can be hard to formalize and communicate because it has personal quality and it is deeply rooted in action and involvement in a specific context. Participatory design has been used actively since the 1980s to involve workers in the design of their own work and work tools (Muller & Kuhn, 1993, Seim & Broberg, 2010).

Virtual reality (VR) technologies are valid tools to support participatory design (PD), because they support common understanding and collaboration among designers and users (Bruno & Muzzupappa, 2010) and other stakeholders (Shen, Ong, & Nee, 2010), and because VR tools enable acquiring feedback during the early product development phases (Leino, 2015; Määttä, 2007).

Knowledge sharing and communication are key aspects in the industrial work context. Knowledge can be defined as a continuum ranging from data via information to knowledge (Mertins, Heisig, & Vorbeck, 2003). Data can be facts of something particular, information is a flow of messages, while knowledge is created and organized by the very flow of information, anchored in the commitment and beliefs of its holders (Nonaka, 1994). Information technology can support the generation of meta-knowledge of who knows what (Choi, Lee, & Yoo, 2010). To improve team performance, organizations must ensure that knowledge is both shared and applied (Choi et al., 2010).

Regarding *training*, a lot of research has recently focused on the concept of Learning Factories (Tisch et al., 2013). Learning Factories pursue an action-oriented approach, with participants acquiring competencies through structured self-learning processes in a production-technological learning environment. Learning Factories thereby integrate different teaching methods with the objective of moving the teaching/learning processes closer to real industrial problems (Tisch et al., 2013). Rentzos, Mavrikios, and Chryssolouris (2015) pointed out that manufacturing training should support the transition from manual work to the future knowledge work. Their teaching factory concept integrates the learning and working environments and thus creates realistic and relevant learning experiences. Interactive involvement and the own actions of the participants facilitate competence development through structured self-learning processes both in learning to solve known problems and in learning problem-solving processes (Tisch, Hertle, Abele, Metternich, & Tenberg, 2016). Mavrikios, Papakostas, Mourtzis, and Chryssolouris (2013) proposed role game-based industrial learning with interactive simulation environments. They claimed that fast and cost-efficient digital training can reduce the need for real hands-on practice and facilitate the integration of a broader range of realistic training scenarios.

Augmented reality (AR) tools are promising both for knowledge sharing and for training. There is a lot of research on AR instructions in industrial work. Earlier research has found that compared to paper-based instructions, AR-based solutions are much faster to use, less errors are made and the operators appear to accept the technology (Baird & Barfield, 1999; Tang, Owen, Biocca, & Mou, 2003; Day, Ferguson, Holt, Hogg, & Gibson, 2005; Henderson & Feiner, 2011; Re & Bordegoni, 2014). Aromaa, Aaltonen, Kaasinen, Elo, and Parkkinen (2016) presented a study in which augmented reality applications were successfully used in knowledge sharing between industrial maintenance technicians. Gonzalez-Franco et al. (2017) showed that training using head-mounted augmented reality devices produced as effective results as person-to-person training.

3. Industrial pilot environments

Our industrial pilots are hosted by the companies Prima Power, Continental and UTC. Prima Power is focused on developing the manufacturing systems that they are providing to their customers, whereas Continental and UTC are focused on developing their own production environment. The pilot cases of Prima Power and Continental are highly automated, whereas the UTC pilot environment includes mainly manual assembly operations. In the following, we describe the three pilot environments and the expectations of the industrial partners for the adaptation solutions. The expectations are based on interviewing experts from each company. Table 1 gives an overview of the three pilot environments.

3.1. Prima Power - efficient customer adoption of multifunctional manufacturing machines

Prima Power is among the four most prominent global specialists in sheet metal working technology, with a comprehensive product range of laser systems and sources, punching, shearing, bending and automation for the sheet metal industry. To increase its automation level, Prima Power has developed their product offering towards multi-functional machines. The integrated machine is built around the production line, where punching, shearing and bending processes are executed automatically in a programmed sequence. This multi-functional machine (Fig. 2) can be operated by a single worker.

The overall system is quite complex in terms of both managing and learning the necessary skills to be able to operate the system. The operators should have smooth and clear user experience. Adaptation of the system is needed to be able to recognize different skills and capabilities of the operators and to provide accordingly information that an individual operator needs to facilitate the production run.

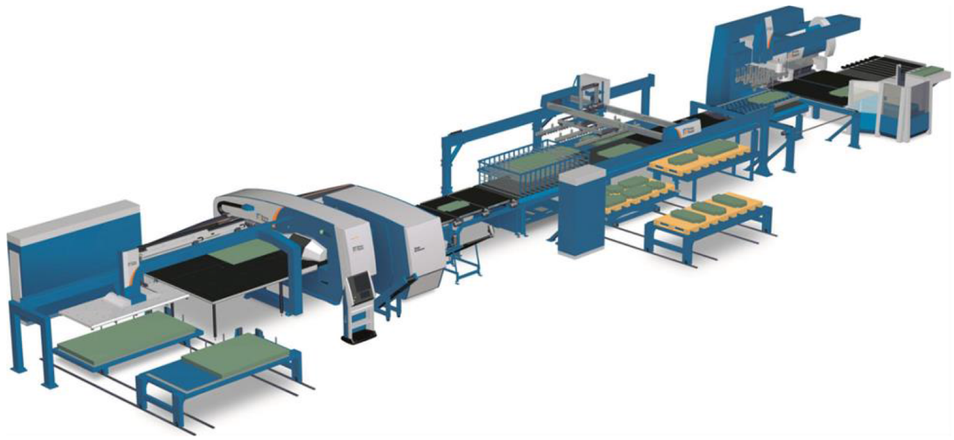

Fig. 2. A multifunctional machine by Prima Power, integrating punching, shearing, buffering and bending machines.

Fig. 3. Continental manufacturing environment: Nozzle body hard machining.

When a customer takes into use a multifunctional machine, the focus is on the line entity rather than on the individual machines. The level of integration should be developed to provide the customer with a comprehensive system view. In addition to adapting the system according to the characteristics of individual operators, adaptation possibilities are seen in adapting the system according to the user role and usage context. In addition, the system should learn from operator behaviour and from how problems have been solved previously.

Currently the operators get basic training well before the system is installed, and then on-site training after the system has been accepted by the customer. A common problem is that the customer is too optimistic in scheduling the start of full production. On-site training takes quite a long time, as it is carried out in parallel with normal production work. In the final phase of the training, the trainer's role is only to be available at the factory for advice. In actual production situations, trainees gradually learn the skills that are needed but the hectic production situations may not allow concentrating on learning. After the training period, the customers frequently need advice for about six months. There is a clear need to make this learning process more efficient.

The training ends after the agreed amount of training has been given. Prima Power would prefer tests to check whether the desired competence level has been reached. They also expect that the training could utilize virtual machinery that would allow training for exceptional situations, especially problem solving.

When customers start to use the machine independently, typical error situations include alarms and machine stops. Problems often arise when customers start manufacturing new products, which require new ways to operate the machine, often generating errors that have not been faced before.

3.2. Continental – increasing the controllability of serial production

Continental Limbach-Oberfrohna is a plant for mass production of injectors for diesel engines in passenger and light commercial vehicles at a very high automation level. For the complex manufacturing process of a diesel injector, around 50 separate sub steps are performed on site. The main goal in order to reach productivity is a continuous workflow without any disturbances: to support the minimization of process interruptions and to decrease the impact of disturbances that cannot be avoided preventively. The key aim is an increase of the controllability and usability of the manufacturing and of the subsidiary processes. Through this, an augmented satisfaction of the process participants can be reached, which will itself lead to a higher level of contribution and therefore to better work results, less production interruptions and faster recovery from disturbances.

The major task for operators and managers in the production is to keep the process under control and in stable condition (Fig. 3). This requires precise and rapid perception, analysis and forwarding of process-relevant information. Even though the information processing is widely automated and already at a high standard, there are still many tasks that need human recognition, decision and input. These activities could be supported with adaptive system features.

Several centralized non-productive functions support the production process control. These functions need to be optimized in order to get full support while spending less effort. Usually several production processes require the support at the same time, which leads to a competition between the processes. Prioritizations must be made all the time, while many different and dynamic criteria and requirements determine the decision. Higher transparency of the priority settings and their publication could contribute to increased acceptance among the customers of central support.

Adaptation solutions could support the allocation of workers to teams by taking into account worker preferences, skills and status as well as the work situation.

Skill enhancement could be supported by modular training. Small and combinable qualification modules (e.g. videos) could be provided to the staff based on their skill profile. The personnel can then themselves decide when and where to train themselves. Knowledge sharing could be supported by allowing the operators to participate in the production of the training modules.

3.3. UTC - increasing work satisfaction and performance in manual assembly work

United Technologies Corp. (UTC) is a diversified company that provides a broad range of high-technology products and services to the global aerospace and building systems industries. Carrier is part of UTC Building & Industrial Systems, a unit of United Technologies Corp., and it is the largest manufacturer and distributor of heating, air conditioning and refrigeration solutions and the global leader in the Heating Ventilation Air Conditioning and Refrigiration (HVACR) industry. The pilot site is Carrier's Air Handling Unit (AHU) assembly workshop in HVAC-Culoz, France. The AHU final assembly workshop consists of a supermarket with 6 work-in-process (WIP) collection points where sub-assemblies are collected and distributed to four equally equipped stations. Each assembly station usually has two workers, one with a high level of experience and the other with low-level experience. Once all the sub-assemblies of an order in one of the WIP collection points are ready, the line supervisor assigns the corresponding assembly order to one of the assembly stations by taking into account the current workload, daily production plan and the matching level of the assembly complexity and the worker skills at the stations.

Due to domination of manual operations in assembly stations, each worker should be flexible enough to move to other assembly stations in order to enhance manufacturing resilience. Hence, any worker should have a structural knowledge of the skills associated with each workstation in order to reduce the amount of time required for solving problems. Therefore, workers must be equipped with the right skills (job enlargement) and should have a good general overview of the whole assembly process (job enrichment, Mital & Pennathur, 2004).

In order to balance and to select the resources involved in the assembly line and to have a better plan for the production of the units, it is important to understand how to re-configure the assembly line based on the worker skills, the type of production, changing demands and the presence of defects. It is important to diagnose variability in the assembly time, driven by the data collected from the assembly line. In order to achieve this objective, it is necessary to have a methodology that is able to make a fusion of different measures coming from sensors located in the assembly work centres and/or wearable sensors. Assignments of assembly orders to different stations should be automatized and must take into account not only task requirements and worker capabilities but also the preferences of workers over different orders.

To reduce the risk of incidents in the working area, it is important to evaluate the safety of the design of the assembly system by identifying risks associated with each area. Hence, each worker should be monitored in order to alert him/her if s/he has not followed the safety practices during his/her tasks. A central system should be able to alert each worker in case of events that are classified as risky.

The worker involved in the assembly process should ensure that the product conforms with the requirements defined during the development of its model. Tools with augmented reality could be adapted for understanding whether the specifications are fulfilled, rather than using CAD drawings, in order to speed up the assembly process and to reduce the total distance travelled between the assembly unit and the table where the CAD drawing stands. The worker should be guided during his/her task by a structural procedure that can be changed according to the model associated with the units. Techniques/tools such as gesture recognition, video analysis and augmented reality could be used to monitor the realization of these tasks as well as to recommend operations/tools to the worker in order to complete their job. Similar to this task, determining the optimal ordering of assembly operations assigned to a worker in terms of total walking distance between assembly unit and the tool magazine for tool changing is another point that can be improved (Öztürk, Tunali, Hnich & Örnek, 2010a), along with finding the most ergonomic and time-efficient way of ordering tasks in terms of task time increments due to positioning of the assembly unit (Öztürk, Tunali, Hnich & Örnek, 2010b). Last but not least, communication channels between workers and with their environment need to be enhanced in order to accommodate knowledge sharing.

4. User studies

In order to study the current context of use at the factories, user requirements, and initial user feedback to the proposed solutions, user studies were carried out in each industrial pilot environment, i.e. Prima Power Customer A, Prima Power Customer B, Continental and UTC. A common interview template was designed and the interviews at each pilot site were designed based on this template. The themes included current work and practices in training, knowledge sharing and participatory design. We also discussed differences between workers and their preferences, as well as first impressions towards worker modelling and adaptation of the manufacturing environment. As the pilot sites are different, the interviews were organized differently at each site, utilizing both individual interviews and focus groups. In the following we describe the method and the results separately for each pilot site.

4.1. Studies with the two customers of Prima Power

4.1.1. Method

We carried out user studies with two Prima Power customers, Customer A and Customer B. The companies had recently started to use new Prima Power multifunctional manufacturing systems, with which they were running highly customized production with short series. Customer A was serving several customers, whereas Customer B was manufacturing parts for their own products.

With Customer A, we interviewed individually five participants (4 male, 1 female) having 1 to 7 years of work experience of the current work. The interviewees either used or monitored the use of the Prima Power line (Fig. 4), having different roles: working as an operator (two persons), a programmer/operator, a production planner and a production manager. The Prima Power line included punching laser machine, loading/unloading and stacking robot, automatic storage system and manufacturing execution system (MES).

With Customer B we interviewed individually eight male employees, including four operators and four people in managerial positions. All operators, with work experience ranging from 3 to 18 years, worked both as programmers, providing digital plans to define the work of the machines ("nesting"), and as operators monitoring and controlling the Prima Power machines. At the Customer B premises, two lines of Prima Power machines provide unique metal pieces, starting from metal sheets, processed with the Prima Power machinery, then

Fig. 4. An operator working with the Prima Power system.

insulated and eventually assembled into finished products in the factory.

The 1-hour semi-structured, audio-recorded interviews were conducted in a meeting room of the factory by two researchers, one mainly leading the interview and the other one making notes and additional questions. The operators and the programmer were also observed for a short time (from half an hour to one hour) while working, to gather contextual understanding of their tasks, work practices, occurring problem situations and the factory environment. All interviewees filled in an information consent form and the participant demographics questionnaire before the interview.

The interview focused on the start-up phase and current use of the machines, on a general level. The interview themes included discussing the workers' experiences of the start-up and training process related to the new line, problems with the use of the machine as well as current practices related to knowledge sharing and design of their work. In addition, we studied their first impressions relating to differences between the factory workers and attitudes towards self-measurements of the workers.

To form a common understanding of the findings, the data of the interviews was first read through by two researchers, and then jointly analyzed by the same researchers. The relevant pieces of data were identified and organized to form data-driven themes. The analysis followed the principles of creating an affinity diagram, an analysis phase of the contextual design method (Beyer & Holtzblatt, 1997).

4.1.2. Results with Customer A

The three interviewed operators were working one at a time in three shifts. The night shift was less hectic than the others, as the easiest jobs were scheduled for the night. The manufacturing jobs were carried out with four separate user interfaces of the individual machines and the storage. In addition, the operators were using a separate software for nesting, i.e. planning the cutting of the pieces from a metal sheet.

The operators had attended a one-week training course at Prima Power Training Centre as well as several shorter training sessions at their own factory. The training sessions were perceived as beneficial in acquiring the initial understanding of the system and its use. However, three interviewees emphasized that actual learning had taken place at work, where the operators had also learned from mistakes. After a couple of weeks of working, the operators felt that they had already learned to use the system well.

The interviewees thought that use of the system was easy, but that recovering from *problem situations* can be challenging. Problems and failures can occur for different reasons, on the manufacturing line, at the automated storage or with the tool station. Support offered by Prima Power was perceived to work rather well. There is a named contact person at Prima Power, and software problems could be resolved via a remote connection. Sometimes the operators sent photographs via email to the Prima Power support service to illustrate the problem situation.

Most interviewees thought that they receive sufficient information and have sufficient tools and practices to *communicate* with others. Face-to-face communication between relevant parties was preferred, and especially error situations were immediately communicated and solved together. Among the operators, the shift change was the most important moment of the workday to share timely issues. In this factory, the machine operator team included only three people, so it is evident that their mutual communication needs were served mostly face-to-face.

The interviewed operators did not see any great *differences* between their personal skills, capabilities or preferences at work. The first spontaneous comment of an operator was: "After all, we are not that different". Another operator pointed out that more support for personal working styles and preferences might lead to situations in which working "with one's own style" would lead to problems in the fluency of the workflow and commonly agreed practices. In this factory, the three operators were chosen to operate the new line because of their previous good work performance. This may be one reason why the operators felt that they were quite similar.

Regarding *work well-being*, the operators reported that they enjoy their work most when the "machine rocks", meaning a situation in which the production line runs fluently without disturbances. Dissatisfaction was related to problem solving, especially when it was difficult to find the cause of the machine stopping. Seeing the work pressure, e.g. as piles of customer orders waiting to be processed, caused stress especially in situations in which the operator could not do anything about the situation e.g. due to mechanical problems.

4.1.3. Results with Customer B

Customer B has two identical lines operated by altogether eight workers in two shifts. The two most experienced operators, however, work in the day shift. The production plan is typically locked for two weeks ahead with full time production. If there is a delay in the production, the operators need to work overtime in order to catch up with the plan. The need for the new machines was raised due to changes in the market: unique products were requested and the series size was close to one. The factory aims to manufacture parts directly for assembly, without intermediate storage. The main change with the new manufacturing machinery was that the factory system could send order data directly to the Prima Power system. At the time of the interviews, the pace of production was still highly unsatisfactory due to frequent error situations that halted the production. However, the quality of the production was assessed to be good, so that the only, albeit notable, shortcoming was the slow production rate due to problems in the functioning of the machines.

The first phase of *training* was organized at Prima Power. That was only classroom training, where Company B's own products were used as examples. The second training phase started in parallel with the installation of the new machines in the factory. During this phase, the trainer was present but he helped the operators only when asked. The possibility was not utilized much, as one of the operators described: "I did not come to ask and do not remember much of the training because I had to keep the manufacturing process going." The company did not want to stop or even reduce production for the training. The amount of training was agreed beforehand but afterwards, the managers thought it would have been better to have agreed on an indicator of sufficient competence level. Finally, both managers and operators commented that training should also have included problem solving, so that the operators would have learned about different errors, error reasons and how to fix the situation.

The system included four *machine interfaces*, each with a different logic, which was considered to be confusing. Especially in the beginning, there were both software errors and mechanical errors on the line. The operators had gradually learned how to solve the most frequent error situations, and they could even predict problems. One operator reported, with relation to the previous and present machinery: "Over the years I have learned to hear from the sound of the machine if something is starting to go wrong." The operators felt that small errors are normal, and cannot really be avoided. However, errors that stop production for longer than one hour should not occur. The purchase manager suggested that a common database of errors to share with Prima Power would have been useful.

In this factory, there is a lot of face-to-face *communication* as the managers are often visiting the factory floor and talking casually with the operators. Two of the operators are exceptionally skillful, and the other operators ask advice from them. If the more experienced workers cannot solve a problem, they contact Prima Power support. Recently, the production manager has organized a system in which the operators report the errors that have occurred during the week. Then every week the two most common errors are discussed in the production meeting with the operators and a common solution to the errors is agreed. Furthermore, the operator team and the production manager have a common WhatsApp group, where they can ask for advice. The operators are willing to help their colleagues even during their leisure time. On the other hand, talking face to face about issues in production has become more difficult. The former factory manager described how times have changed: "In the old days we used to have coffee together. Then you could informally tell what will be happening in the production next week. People were open to describing problems and getting advice. Now you have to organize a meeting and people are not so willing to share problems in there".

In this factory there were clear *differences* in the competence levels of the operators. Two operators were more skilled and they were eager and devoted to problem solving. The former factory manager described the differences: "All can use the machines but problem-solving - others do not even want to learn it, others are eager to learn the whole inner life of the machines." The interviewees thought that learning could be supported by adaptation: simple interfaces for beginners and more complex ones for experts. Furthermore, a safety mode for novice operators was suggested, to prevent actions that might lead to severe breakage.

Interviewees were also asked about their opinions about *operator monitoring* - heart rate, number of steps and the like. Some managers were cautious about the idea, anticipating operators' reluctance about it, whereas some found it interesting and useful, either because they used physical health monitoring during leisure time themselves, or because they were interested in learning how that information could be combined with production efficiency. Similarly, two operators considered monitoring as something they do not want to use at least at their working place, whereas two operators considered it an interesting option. The reason for the different opinions among operators could be the difficult working situation with an inappropriate level of production and heavy workload. The operators with a positive attitude were the ones who were recognized as good operators, having such benefits at work that other operators did not have. Thus, these operators could "afford" monitoring as they could be sure it would not be used against them. As a whole, it can be considered that the anonymity of monitoring results is of primary importance, and if operators do not know very clearly how the results would be used, they are easily against it.

4.2. Studies at continental

4.2.1. Method

In order to investigate the actual problems that potentially decrease work satisfaction and to identify points for further improvement, we conducted four focus groups and an interview with two members of the work council. In each focus group and the interview, one researcher acted as moderator or interviewer and the other one made notes. The focus groups and the interview were audio-recorded. All participants signed the informed consent form, and focus group members filled out a short questionnaire including age group, gender and profession.

The four semi-structured focus groups convened in a meeting room at the factory. In sum, 21 employees from Continental (3 female, 18 male) participated. The sample represented different age groups (26–35 years: 28%; 36–45 years: 48%; 46–55 years: 24%) and consisted of engineers, quality control inspectors, operators, shift foremen, etc. from different company departments and units. They were rewarded with three vouchers for lunch in the company's cafeteria.

Within the 2-hour focus groups, problems occurring during daily work were collected with notes and a pin chart, specified and discussed after briefly introducing the project. Then, potential solutions were gathered and, at the end of this first session, the relevance of the different, raised topics considering further improvement was evaluated using a point system. After this first task, the moderator started discussion on additional reasons that could reduce work satisfaction, existing ways of user engagement and, if there was time at the end, the potential of adaptive automation.

The 1-hour semi-structured interview with 2–3 members of the work council was conducted in their office. One participant had to leave in the middle of the interview. Topics raised were also potential problems in the work context, factors reducing worker satisfaction, potential solutions to increase satisfaction, worker engagement, and adaptive automation.

The data from the focus groups and the interview was mainly analyzed qualitatively, except for the distributed dots that were intended to identify major problems. The extended notes and the pin chart results were read by two researchers in order to deepen their understanding. Then, data-driven sub-categories were identified and analyzed according to thematic analyses by Braun and Clarke (2006).

4.2.2. Focus group results

Statements from all four focus groups were analyzed comprehensively and the results represent a summary of all groups. The focus groups revealed several main topics for expected improvement, such as information and communication, working conditions and shift-working, worker involvement, social aspects as well as worker education.

Working conditions and shift-working appeared to raise problems for participants across all focus groups. Many of the registered problems (n = 29) could be summarized as belonging to this category. Problems reflecting working conditions and shift-working got the most votes for being major problems for job satisfaction (22 points). Participants reported, for example, inconsistent shift models varying in number of shifts per month, and weekend shifts. These factors negatively influence workers' social life and health. In general, planning shifts is challenging and no general tool exists. Thus, expectations on future developments against the background of industry 4.0 and the digitalization of factory production aim at improving this situation.

In terms of working conditions, participants stated that some work tasks are not very ergonomic. Occasionally, supportive technology such as lifting aids exists, but is not used due to the time pressure in production. Some work places, especially those in open-plan offices, have a high noise level, which can be very disturbing when intense concentration is needed. Workers also emphasized the importance of obtaining the possibility to organize their workplaces themselves. In addition, participants stated that they are stressed because of high workload, changing priorities, bad smell and vibrations or challenges when they have to work in different units or with not commonly used machines.

Information and communication received much attention (26 notes, 18 points highlighting major problems) from the participants. Gathering and communicating performance parameters of the process turned out to be very time-consuming, as it involves several documentation types and forms (digital and paper), and a lot of paper work that is time-consuming and restricted in the amount of presentable information. Additionally, the need for further information was communicated (e.g., availability of co-workers from other work units; handling/problem solving for machines not in regular use), and more interconnection was called for between the different information gathering systems as well as between the different work units. The need for more knowledge and information is especially high when switching between units (different machines, interfaces). As potential solutions, participants requested to increase transparency by providing access to the intranet, improving the communication with superiors and the utilization of digital, connected systems including access to machines and data via wearable devices (i.e., smartwatch), tablets or computers. Additionally, knowledge sharing should become easier and more generalized. Existing knowledge databases are forgotten or hard to find (when there is access to the intranet), new solutions can improve this. Finally, yet importantly, information sharing as a whole could be improved for the whole production process in order to show the relevance of workers' own work and the work of others.

Involvement of workers seemed to be of less relevance when discussing daily hassles during work (4 notes, 2 points marking it as a major problem). Workers reported the impression that a lot of problem solving takes place without them, although they would like to be involved more and have higher degrees of freedom in decision making. Currently, workers can suggest improvements via a digital tool for collecting labour-saving proposals, but the follow-up process is slow and not always transparent. For the people dealing with the suggestions for improving tools or processes, the implemented system is time-consuming and its functionality could be improved. Some participants also reported that they can contribute to purchase decisions of new machines, but often financial aspects have a higher impact on decisions and workers feel that their advice is not given sufficient weight in the final decision. Participants further stated that they should be more involved in the organization of their workplace, and some workers would like to have a choice on which machine to work on. Based on experiences with existing solutions, transparency of decisions after engaging the worker is of prime importance and should be improved in future solutions.

Participants within two groups reported that further *training* of the workers is based mostly on their own initiative and some feel not really supported in their attempts. Additionally, few possibilities appeared to exist to get promoted from fabrication jobs. It was further mentioned that training for interacting with new software should be enhanced; existing knowledge gets lost and knowledge-sharing systems are often either not known or not easily accessible. In one group, an existing project for training workers was mentioned. This represents a good basis for further developing steps. However, the relevance of training should be made transparent to the workers. Additionally, once trained, the workers should get the chance to utilize their new competences.

Within two focus groups, workers described *social problems* of lack of solidarity and understanding for each other, partly a dog-eats-dog mentality, and impoliteness between workers. Some participants stated that there is a lack of understanding within the company. New solutions for communication and information sharing could provide a better insight into the whole process in order to increase reciprocal understanding of each other's work and its challenges and thus alleviate social problems.

At the end of the focus groups, the question about *adaptive automation* was discussed. Workers had difficulties imagining how this could be implemented. A few suggestions were made, including the adaptation of automation to the workers' preferences in terms of the machine they want to work with, and working times and workers' abilities. Therefore, a future production planning system should include these factors when scheduling the work.

4.2.3. Interview results of the work council

The interview with the work council members revealed many points that were also raised in the focus groups: The changes in the shift-model and the production-centered shift plans are challenging for family life planning and reduce satisfaction. Worker involvement exists, but needs improvement. New ways of user engagement and participatory design are already implemented to find a better fitting solution to increase the ergonomic factors of work. They also underpin the statements collected in the focus groups that workers have very limited opportunities to use newly gained knowledge or competences after further training. An interesting point for future development is that measuring the performance of the worker and assessment of physiological data are critical issues. The work council does not accept these measurements if the employer has access to this data, but if the data stays only with the worker it is worth testing its value. In sum, the work council supports the implementation of new technology and smart devices, which are already involved in test pilots.

4.3. Studies at UTC

4.3.1. Method

To gather the requirements and understand the UTC workers' expectations, a user study was conducted in HVAC-Culoz, particularly at the assembly stations of the Air Handling Unit. The study consisted of ten interviews with a representative group of workers. Workers with various job roles including a line manager, a team leader, a team coordinator, a quality controller, and six assembly workers were interviewed. Equal numbers of novice and expert workers were sampled. The common questionnaire was translated to French by two researchers. Each worker received a copy of the questions one week before the interview session. Each interview session took one hour, including explaining of the questions and then discussions between one researcher and the respective employee. Results of the interviews were analyzed and translated to English by the same two researchers.

4.3.2. Results of the user studies

Regarding work satisfaction and dissatisfaction, all participants underlined three main aspects in their workplace which they are pleased with, including the work environment, the work organization, and an interesting job without monotony. However, workers depicted several factors that need to be improved, primarily classified as ergonomic and operational issues. Regarding the ergonomics, workers reported criticism of the lighting system and working posture. They spend their working hours standing and the lighting system is not satisfactory for certain tasks. Workers highlighted three operational concerns that should be improved: modernizing the tool magazine, not receiving correct parts due to lack of communication with sub-assembly lines and incomplete assembly schemata that are experienced with some job orders. Workers mentioned that using new technologies such as 3D screens for assembly schemata, knowledge sharing platforms for improving communication in the plant material supply system would certainly improve their work satisfaction and eventually the quality of their work.

Some of the participants highlighted that not all workers have the same level of expertise and do not all perform the same tasks. Therefore an adaptive *training* strategy should be used to develop workers' competence with the skills they need. By analyzing their skill profiles, personalized training plans can be proposed. It was further mentioned that maintaining the skills based on workers' profiles would help in improving on-boarding new workers and rapid up-skilling of existing workers. Regarding *knowledge sharing*, the participants would like to have a better platform/solution to replace the open discussions so that they could ask for the information when it is needed.

Without any exceptions, all the participants showed resistance towards *monitoring* of their behavior. They mentioned that this kind of instrumentation is a source of stress and panic. The most optimistic participant agreed that this monitoring may bring some improvement to the assembly line, but s/he stressed that the collected information should not be used in any way to measure or evaluate the productivity or the performance of the workers.

4.4. Analysis of the results

With the two Prima Power customers, a major challenge for the operators is to keep the highly automatized production lines running to process efficiently the customer orders. Operator work is focused on efficient production change and problem solving to keep the machine running. Both customers had recently taken into use new Prima Power multi-function lines, and major development needs were identified in efficient training and on-the-job learning.

At the Continental site, the main focus of the operators' work is to minimize process interruptions and to minimize the effects of disturbances, thus keeping the process under control and in stable condition. This work is supported by gathering, processing and providing relevant information, mainly automatically. Several support functions, such as the measurement lab, support the production and these functions are common to several production processes. Thus, prioritization of support requests is needed. The openness regarding new technology

Table 2
An overview of the expectations and concerns towards the Operator 4.0 solutions.

Solution	Expectations	Concerns
Empowering adaptation solutions based on dynamic worker models	Compensation of differences in competence levels "Safety mode" for novice workers Adaptive training Adaptation in planning shifts, taking into account worker preferences	Standard work practices vs. working with one's own personal style
Empowering feedback on well-being and performance	Receiving positive feedback	Negative influence of comparing workers Measures as potential sources of stress Data privacy and security
Engagement with participatory design	Increased commitment of workers Utilising worker expertise to achieve better design Better insight into the process	How much influence can the workers have on their work Insufficient transparency of changes could demotivate workers
Engagement with knowledge sharing	Storing informally shared knowledge Integrating information from different sources and making it easily accessible An easily available platform for discussions	Previous experiences with knowledge sharing tools that were not used regularly
Engaging training	Support for learning by doing Learning problem-solving Adaptive training according to competence level	Limited possibilities to utilize and maintain new skills

from the side of the worker and the workers' council exists in general and is an important pre-condition for future acceptance of our solutions.

At the UTC pilot site, only human operators work at assembly stations. As different skills are needed at different assembly stations and with different orders, training is important as well as planning the production to fit together available machines, task requirements, worker capabilities and worker preferences. Development potential is seen in assembly guidance that is currently based on paper-based CAD drawings that the operators need to check regularly.

In Table 2, we present an analysis of the results, highlighting the expectations as well as the concerns of the factory workers relating to the proposed solutions.

Adaptation was seen to be useful at almost all the pilot sites. At Prima Power Customer A the two operators thought they were quite similar, but at all the other pilot sites the operators acknowledged that there were many differences between workers. These differences in competence levels could be supported by adaptation, e.g. with a "safety mode" for novice workers. However, supporting several parallel ways of working instead of standard work practices was considered a potential source of problems. Planning work shifts is a complex task which adaptation could support, as was recognized both at Continental and at UTC. At Continental the workers stressed that it is important to include preferences for co-workers, shifts and machines in addition to abilities and competences in worker modelling and adaptation approaches. Adaptation needs were also identified in training, in which each worker could be supported in developing his/her competences at an individually adapted rate.

The factory workers were not very keen on the idea of measuring workers. The idea raised negative expectations of highlighting differences between workers and comparing their efficiency at work. Measuring the performance of individual workers was seen as a potential source of stress. For worker modelling, physiological data can be gathered, but data security issues need to be addressed and the data rights should stay with the user.

With both Prima Power customers, the attitude of the management was open and positive towards *participatory design*. It was expected to improve the commitment of workers and utilize their expertise to achieve better results. However, at Customer A, the operators felt that almost all issues are determined by the machines or the customer orders, and that this decreases the possibilities to have an impact on one's work. In the Continental case, the workers also felt that a lot of problem-solving takes place without their involvement, even if they would like to contribute, or that their advice is not given sufficient weight in decision making. At UTC, seven out of the ten interviewees reported that they had never participated in workplace design. Participatory design was seen as promising at all the pilot factories, as it could reduce daily problems and give a better insight for the workers into the process. Transparency of the design decisions is important, so that people can see how their contribution has been utilized.

At the pilot sites, there were some knowledge sharing systems in use but they were not used regularly. Shift change is a natural situation for face-to-face *knowledge sharing* but in these situations, the knowledge shared is not always stored or not all the important information is shared. Often help and support is also needed during the shift, especially in error situations, and then fellow workers are not always available face to face. Some solutions were also in use for informal knowledge sharing, e.g. WhatsApp with the Prima Power customer service team as well as with the operators at their Customer B. In the Continental case, information is gathered from several sources, making communication time-consuming, and sometimes information is lost. Existing knowledge sharing systems are often not known or they are not easily accessible. At UTC, the workers also commented that a suitable platform could replace the open discussions.

At each pilot site the interviewed workers emphasized the importance of *learning* by doing. General training is useful in acquiring initial understanding and an insight into the overall process. Problem solving skills are important, and they can be learned only in practice. At the Prima Power Customer A and at Continental, the interviewees emphasized the differences in competence levels and the importance of adaptive training based on worker's current skills and the skills needed in the future. At Continental the interviewees emphasized that it is important to be able to utilise newly learned skills immediately after the training. Similarly, the UTC interviewees stressed the importance of maintaining the achieved skills.

The interviewees had positive expectations towards all the proposed solutions. However, there were many concerns regarding measuring the workers. Positive and encouraging feedback would be welcome, as currently measures and feedback were felt as potential sources of stress. The concerns relating to the other solutions were often related to practices at the workplace, which highlights the importance of developing new tools and new work practices in parallel. The user studies revealed many aspects that could be addressed and improved by future solutions to improve both work well-being and work performance. In the following section we describe how we have interpreted the results into design implications.

5. Design implications

5.1. Empowering the worker

Adaptation of the production environment has potential in compensating the differences in worker competence levels, and supporting gradual learning. Adaptation of the manufacturing environment can take place on three levels: machine user interface (situational view), machine behaviour (parameters, task lists, recovering error situations) and production planning (optimal machine and operator entity to run the production orders). We could identify needs for all these kinds of adaptation.

Adaptation could be utilized in help systems of the machines and wizard type operations e.g. in machine programming. In information processing adaptation can include a role-based data entering mask as well as showing situationally relevant information as proposed in the Continental case.

Adaptation of the manufacturing system should facilitate identifying operator role, skills and capabilities as well as the production situation in order to provide information and support needed in the specific situation. Based on worker profile and adaptation, the user interfaces of the machines could adapt to allow only such functions that the worker is mastering. Adaptation should serve both user interfaces of individual machines and a systemic view of the machine entity. The aim should be a smooth and clear user experience.

In both the Continental and UTC cases, planning work shifts was reported to be challenging. Adaptive production planning should take into account available machines, task requirements, worker capabilities as well as worker preferences e.g. regarding which machines they would like to work, or preferred shifts. Adaptive production planning can also include prioritization of support functions as suggested in the Continental case. Implementation of the Smarter Operator (Romero, Stahre, et al., 2016) would help to realize this.

A dynamic database of workers and their competencies would help in work planning to find competent workers for each task (enabling the realization of the Analytical Operator (Romero, Stahre, et al., 2016)). The database would also support monitoring the individual competence development of each worker.

The negative expectations of the workers towards measuring worker-related (personal) data were based on previous experiences, so in our work it will be important to involve the workers in the design process. Even if the measures would be used for adaptation, feedback of the measures should be shown only to the worker him/herself. The workers should accept that data is collected from them and how the data will be used, so that the Healthy Operator (Romero, Stahre, et al., 2016) could be realized. This is also in line with the new GDPR regulation (European Union, 2018). Measures should not be used to monitor the performance of individual workers.

The workers would benefit from positive feedback in situations in which the production runs smoothly, to concretize their success and show the positive flow. Daily production goals could be made visible and it could be shown how they are being achieved. Visualizing the production flow as well as the problems faced and solved would also support maintaining an overview of the daily production.

5.2. Engaging the work community

Participatory design raised very positive feedback with most interviewees. In all the pilot cases participatory design seems to have potential benefits. The concerns regarding the actual possibilities to influence should be taken into account by identifying the potential areas where participatory design could have actual influence. Virtual reality tools can support participatory design by illustrating planned production processes.

The user studies revealed needs to develop *knowledge sharing* tools that are described as part of the Social Operator (Romero, Stahre, et al., 2016). An easily accessible platform for knowledge sharing would ensure that everyone has access to a common knowledge base. It might also evolve into a place where good work practices and ways to solve problems are shared within the work community and maybe even with work machine providers, as in the Prima Power case. This would also serve the development of customer understanding at Prima Power. Knowledge sharing tools should be easily accessible. Augmented reality tools, as proposed for the Augmented Operator (Romero, Stahre, et al., 2016), can support connecting the discussions to the actual production environment. The workers should be encouraged to contribute. Gamification solutions could be utilized to that end. Knowledge sharing tools should be integrated to existing information systems, so that they extend them with worker knowledge.

In the Prima Power case, a clear need for the Virtual Operator (Romero, Stahre, et al., 2016) using a virtual factory-based *training* environment was identified by both Prima Power personnel and their customers. The virtual factory would facilitate training problem solving skills in realistic problem situations. As each customer site is different, it is important to customize the training environment according to the customer. Virtual factory-based training can be utilized well before the actual production line is in use and the training environment can be updated with actual problem situations as they are faced. The training environment should support both the system view and the operation of individual machines.

Continental proposes a concept of “plug and learn” which enables the Social Operator (Romero, Stahre, et al., 2016): workers can utilize qualification modules produced by other workers to develop their competence at their own pace. Completed training sessions can be shown in worker knowledge base and qualification modules can be proposed to workers based on their role. Video-based training, a profiled training plan and monitoring the progress of skills were suggested in the UTC case. A training strategy should analyse the skill profiles of the workers and propose adequate training. After training, the worker should be given opportunities to utilize the newly acquired knowledge.

To satisfy the knowledge and information needs while engaging the work community, a combined type of Social, Augmented and Virtual Operator seems promising.

6. Discussion

The Industry 4.0 revolution (Kagermann et al., 2013) was already influencing the factories that we studied. Prima Power and Continental pilot environments are highly automated and the operators’ work consisted mainly of monitoring the machines and problem-solving. The customers of Prima Power were already manufacturing very short customized series. However, compared to Operator 4.0 visions, the operators did not have many possibilities to utilize and develop their creative, innovative and improvisational skills, as suggested by Romero et al. (2016). The potential of integrating physical and virtual reality (Gorecky et al., 2014; Romero, Bernus et al., 2016; Longo et al., 2017) was acknowledged, but actual implementations were still missing. The results indicate that implementation of the Smarter, Augmented, Virtual, Social and Analytical Operator (Romero, Stahre, et al., 2016) could solve various problems and support engaging and empowering workers. However, the Healthy Operator (Romero, Stahre, et al., 2016) is a type of Operator that is not welcomed by every worker as it is connected with the assessment of personal data related to well-being or performance.

As suggested by earlier research, we identified needs for supporting work engagement (Maslach & Leiter, 1997) and for getting positive feedback of one’s own work (Obrist, Reitberger, Wurhofer, Förster, & Tscheligi, 2011). Currently work seemed to be fragmented and thus did not allow engagement. When discussing feedback, most workers thought about negative feedback. They were not used to receiving positive feedback from their work. The quantified worker approach (Heikkilä et al., 2018), in which the worker gets positive feedback from his/her own performance and achievements, seemed thus quite welcome. However, worker measuring and modelling raises many doubts within workers and also with factory management. Therefore it is important to make early demonstrators of the ideas and to share them with the employees to design the ideas further with them in order to find acceptable and ethically sustainable solutions. Earlier studies (Mattila et al., 2013) showed that even if employee monitoring is accepted, the usage often declines after some initial enthusiasm. This highlights the need to develop solutions that support sustained use.

As two of our sites were highly automated and one focused on manual assembly, we did not identify needs for adapting the level of automation as proposed by Johansson et al. (2009). Otherwise the identified adaptation needs are in line with what has been proposed in earlier studies. Needs for adaptation to human skills (Heilala & Voho, 1997) were identified especially in training. In the Continental and UTC cases we identified needs for worker skill and preference-based adaptation in production planning, as proposed by Jaturanonda and Nanthavanij (2011) and Colucci et al. (2004). Adaptation needs were also identified in user interfaces, as proposed by Rothrock et al. (2002).

Virtual factories have been proposed by several researchers as platforms for participatory design (Bruno & Muzzupappa, 2010; Shen et al., 2010; Ma et al., 2011; Määttä, 2007). In our cases, participatory design was expected to improve the commitment of workers and utilize their expertise to achieve better results. The workers would like to be more involved in the work place and production design, and they thought that participation would decrease the problems that they face in their work. However, there were also doubts regarding whether they really could have possibilities to impact on their work. The potential of virtual factory platforms should be utilized to develop engaging and influential participatory design practices.

In all the pilot sites, the interviewees saw that there existed tacit knowledge (Nonaka, 1994) that should be made visible and shared. In the pilot sites, some solutions were already in use for informal knowledge sharing but the need for more developed systems was identified. An easily accessible platform for knowledge sharing could evolve into a place where good work practices and ways to solve problems are shared within the work community but also with work machine providers and other stakeholders.

In line with the learning factories concept (Tisch et al., 2013; Rentzos et al., 2015), the interviewees saw that the virtual factory would facilitate training problem solving skills in realistic problem situations, including both access to potential solutions and guidance in the problem solving process. As each customer site is different, it is important to customize the training environment according to the customer. Virtual factory-based training can be utilized well before the actual production line is in use and the training environment can be updated with actual problem situations and suggested solutions as they are faced. Another approach to training was also identified: the plug and learn concept, in which workers can themselves produce video-based qualification modules to be shared with peers. A module-based training approach would facilitate learning at the worker's own pace.

Many concerns of the workers were related to work practices at the work place. When developing the solutions it is important to keep workers involved and to develop the work practices in parallel with the technical solutions to empower workers and to engage the work community. People are different, and not all workers are or need to be active in sharing knowledge and in participatory design. Only such Operator 4.0 solutions that support smooth work practices and workers' individuality have potential to be adopted to long term actual use.

7. Future work

Our work has continued by defining application concepts of solutions to empower the worker and solutions to engage the work community. The identified user expectations and concerns have been utilized in choosing the concepts to be developed further and refining them in collaboration with all project partners. The use cases have been illustrated so that we have been able to evaluate them with operators and other stakeholders and also to use them in participatory design activities. At the time of finalizing this paper we are about to start long-term industrial pilots of the developed concepts.

Acknowledgements

The research was funded under the European Commission's H2020 framework programme in the project Factory2Fit "Empowering and Participatory Adaptation of Factory Automation to Fit for Workers" (Grant agreement 723277). The authors are grateful to all the researchers and company representatives who contributed to and supported the work presented in this publication.

References

Aromaa, S., Aaltonen, I., Kaasinen, E., Elo, J., & Parkkinen, I. (2016). Use of wearable and augmented reality technologies in industrial maintenance work. *Proceedings of the 20th international academic Mindtrek conference* (pp. 235–242). ACM.
Baird, K. M., & Barfield, W. (1999). Evaluating the effectiveness of augmented reality displays for a manual assembly task. *Virtual Reality, 4*(4), 250–259.
Beyer, H., & Holtzblatt, K. (1997). *Contextual design: Defining customer-centered systems.* Elsevier.
Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa.
Bruno, F., & Muzzupappa, M. (2010). Product interface design: A participatory approach based on virtual reality. *International Journal of Human-Computer Studies, 68*(5), 254–269. https://doi.org/10.1016/j.ijhcs.2009.12.004.
Chen, T. Y., Huang, Y. C., Chou, T. S., Shih, C. S., & Liu, J. W. (2012). Model-based development of user-centric automation and assistive devices/systems. *IEEE Systems Journal, 6*(3), 388–400.
Choi, S. Y., Lee, H., & Yoo, Y. (2010). The impact of information technology and transactive memory systems on knowledge sharing, application, and team performance: A field study. *MIS Quarterly,* 855–870.
Colucci, S., Noia, T., Sciascio, E., Donini, F., Mongiello, M., & Pisticelli, G. (2004). Semantic-based approach to task assignment of individual profiles. *Journal of Universal Computer Science, 10*(6), 723–731.
Day, P. N., Ferguson, G., Holt, P. O. B., Hogg, S., & Gibson, D. (2005). Wearable augmented virtual reality for enhancing information delivery in high precision defence assembly: An engineering case study. *Virtual Reality, 8*(3), 177–184. https://doi.org/10.1007/s10055-004-0147-8.
Edwards, K., & Jensen, P. L. (2014). Design of systems for productivity and well being. *Applied Ergonomics, 45*(1), 26–32.
Ehn, P. (1993). Scandinavian design: On participation and skill. *Participatory Design: Principles and Practices,* 41–77.
ElMaraghy, H. A. (2005). Flexible and reconfigurable manufacturing systems paradigms. *International Journal of Flexible Manufacturing Systems, 17*(4), 261–276.
European Union (2018). The general data protection regulation (GDPR) (EU) 2016/679.
Gonzalez-Franco, M., Pizarro, R., Cermeron, J., Li, K., Thorn, J., Hutabarat, W., ... Bermell-Garcia, P. (2017). Immersive mixed reality for manufacturing training. *Frontiers in Robotics and AI, 4,* 3.
Gorecky, D., Schmitt, M., Loskyll, M., & Zühlke, D. (2014). Human-machine-interaction in the industry 4.0 era. *12th IEEE international conference on industrial informatics (INDIN), IEEE, 2014, July* (pp. 289–294). IEEE.
Goryachev, A., Kozhevnikov, S., Kolbova, E., Kuznetsov, O., Simonova, E., Skobelev, P., ... Shepilov, Y. (2013). "Smart factory": Intelligent system for workshop resource allocation, scheduling, optimization and controlling in real time. *Advanced materials research* (pp. 508–513). Trans Tech Publications.
Heikkilä, P., Honka, A., & Kaasinen, E. (2018). Quantified factory worker: designing a worker feedback dashboard. *10th Nordic conference on human-computer interaction (NordiCHI '18)* (pp. 515–523). New York, NY, USA: ACM.
Heilala, J., & Voho, P. (1997). Human touch to efficient modular assembly system. *Assembly Automation, 17*(4), 298–302.
Henderson, S. J., & Feiner, S. K. (2011). Augmented reality in the psychomotor phase of a procedural task. *Mixed and augmented reality (ISMAR), 2011 10th IEEE international symposium on* (pp. 191–200). IEEE.
Jain, A., Jain, P. K., Chan, F. T., & Singh, S. (2013). A review on manufacturing flexibility. *International Journal of Production Research, 51*(19), 5946–5970.
Järvenpää, E. (2012). Capability-based adaptation of production systems in a changing environment. Doctoral thesis. Tampere University of Technology. Publication, Vuosikerta. 1082, Tampere University of Technology, Tampere.
Jaturanonda, C., & Nanthavanij, S. (2011). Analytic-based decision analysis tool for employee-job assignments based on competency and job preference. *Industrial Journal of Industrial Engineering, 18*(2), 58–70.
Johansson, B., Fasth, Å., Stahre, J., Heilala, J., Leong, S., Lee, Y. T., & Riddick, F. (2009). Enabling flexible manufacturing systems by using level of automation as design parameter. *Winter simulation conference* (pp. 2176–2184). Winter Simulation Conference Retrieved from http://www.informs-sim.org/wsc09papers/209.pdf.
Kagermann, H., Wahlster, W., & Helbig, J. (2013). Securing the future of German

manufacturing industry. Recommendations for implementing the strategic initiative INDUSTRIE 4.0, final report of the Industrie 4.0 Working Group, Forschungsunion.

Lasi, H., Fettke, P., Kemper, H. G., Feld, T., & Hoffmann, M. (2014). Industry 4.0. *Business & Information Systems Engineering, 6*(4), 239–242.

Leino, S.-P. (2015). Reframing the value of virtual prototyping. Intermediary virtual prototyping - the evolving approach of virtual environments based virtual prototyping in the context of new product development and low volume production. VTT, Espoo.

Leung, Y.-T. (2004). *Handbook of scheduling: Algorithms, models and performance analysis.* London: Chapman & Hall. London.

Locke, E. A. (1976). The nature and causes of job satisfaction. In M. D. Dunnette (Ed.). *Handbook of industrial and organizational psychology* (pp. 1297–1349). Chicago: Rand McNally.

Longo, F., Nicoletti, L., & Padovano, A. (2017). Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context. *Computers & Industrial Engineering, 113*, 144–159.

Ma, D., Zhen, X., Hu, Y., Wu, D., Fan, X., & Zhu, H. (2011). Collaborative virtual assembly operation simulation and its application. In D. Ma, J. Gausemeier, X. Fan, & M. Grafe (Eds.). *Virtual reality & augmented reality in industry* (pp. 55–82). Berlin: Springer.

Määttä, T. J. (2007). Virtual environments in machinery safety analysis and participatory ergonomics. *Human Factors and Ergonomics in Manufacturing & Service Industries, 17*(5), 435–443.

MacDougall, W. (2014). Industrie 4.0: Smart manufacturing for the future. Germany Trade & Invest.

Maslach, C., & Leiter, M. P. (1997). *The truth about burnout.* San Francisco: Jossey-Bass.

Mattila, E., Orsama, A. L., Ahtinen, A., Hopsu, L., Leino, T., & Korhonen, I. (2013). Personal health technologies in employee health promotion: Usage activity, usefulness, and health-related outcomes in a 1-year randomized controlled trial. *JMIR mHealth and uHealth, 1*(2).

Mavrikios, D., Papakostas, N., Mourtzis, D., & Chryssolouris, G. (2013). On industrial learning and training for the factories of the future: A conceptual, cognitive and technology framework. *Journal of Intelligent Manufacturing, 24*(3), 473–485.

Mertins, K., Heisig, P., & Vorbeck, J. (2003). *Knowledge management: Concepts and best practices.* Springer Science & Business Media.

Mital, A., & Pennathur, A. (2004). Advanced technologies and humans in manufacturing workplaces: An interdependent relationship. *International Journal of Industrial Ergonomics, 33*, 295–313.

Mourtzis, D., & Doukas, M. (2014). The evolution of manufacturing systems: From craftsmanship to the era of customisation. *Handbook of research on design and management of lean production systems* (pp. 1–29). IGI Global.

Muller, M. J., & Kuhn, S. (1993). Participatory design. *Communications of the ACM, 36*(6), 24–28.

Nonaka, I. (1994). A dynamic theory of organizational knowledge creation. *Organization Science, 5*(1), 14–37.

Novak-Marcincin, J., Barna, J., Janak, M., & Novakova-Marcincinova, L. (2013). Augmented reality aided manufacturing. *Procedia Computer Science, 25*, 23–31.

Obrist, M., Reitberger, W., Wurhofer, D., Förster, F., & Tscheligi, M. (2011). User experience research in the semiconductor factory: A contradiction? *IFIP conference on human-computer interaction* (pp. 144–151). Berlin, Heidelberg: Springer September.

Öztürk, C., Tunalı, S., Hnich, B., & Örnek, A. (2010). Simultaneous balancing and scheduling of flexible mixed model assembly lines with sequence dependent task time increments. In Kasımbeyli, R., Dinçer, C., Özpeynirci, S., Sakalauskas, L. (Eds.), MEC EurOPT 2010 Selected papers, (pp. 237–240). Vilnius, ISBN 978-9955-28-598-4.

Öztürk, C., Tunali, S., Hnich, B., & Örnek, A. M. (2010a). Simultaneous balancing and scheduling of flexible mixed model assembly lines with sequence-dependent setup times. *Electronic Notes in Discrete Mathematics, 36*, 65–72.

Radziwon, A., Bilberg, A., Bogers, M., & Madsen, E. S. (2014). The smart factory: Exploring adaptive and flexible manufacturing solutions. *Procedia Engineering, 69*, 1184–1190.

Re, G. M., & Bordegoni, M. (2014). An augmented reality framework for supporting and monitoring operators during maintenance tasks. *International conference on virtual, augmented and mixed reality* (pp. 443–454). Cham: Springer.

Rentzos, L., Mavrikios, D., & Chryssolouris, G. (2015). A two-way knowledge interaction in manufacturing education: The teaching factory. *Procedia CIRP, 32*, 31–35.

Romero, D., Bernus, P., Noran, O., Stahre, J., & Fast-Berglund, Å. (2016). The operator 4.0: human cyber-physical systems & adaptive automation towards human-automation symbiosis work systems. *IFIP international conference on advances in production management systems* (pp. 677–686). Cham: Springer.

Romero, D., Stahre, J., Wuest, T., Noran, O., Bernus, P., Fast-Berglund, Å., & Gorecky, D. (2016, October). Towards an operator 4.0 typology: a human-centric perspective on the fourth industrial revolution technologies. In International conference on computers & industrial engineering (CIE46) (pp. 1–11).

Rothrock, L., Koubek, R., Fuchs, F., Haas, M., & Salvendy, G. (2002). Review and reappraisal of adaptive interfaces: Toward biologically inspired paradigms. *Theoretical Issues in Ergonomics Science, 3*(1), 47–84.

Saari, L. M., & Judge, T. A. (2004). Employee attitudes and job satisfaction. Human resource management: Published in cooperation with the school of business administration, The University of Michigan and in alliance with the society of human resources management, 43(4), 395–407.

Schaufeli, W. B., & Bakker, A. B. (2010). Defining and measuring work engagement: Bringing clarity to the concept. In A. B. Bakker, & M. P. Leiter (Eds.). *Work engagement. A handbook of essential theory and research*. Psychology Press.

Schaufeli, W. B., Salanova, M., González-Romá, V., & Bakker, A. B. (2002). The measurement of engagement and burnout: A two sample confirmatory factor analytic approach. *Journal of Happiness Studies, 33*(1), 71–92.

Seim, R., & Broberg, O. (2010). Participatory workspace design: A new approach for ergonomists? *Industrial Journal of Industrial Ergonomics, 40*, 25–33.

Shen, Y., Ong, S. K., & Nee, A. Y. (2010). Augmented reality for collaborative product design and development. *Design Studies, 31*(2), 118–145.

Shpilevoy, V., Shishov, A., Skobelev, P., Kolbova, E., Kazanskaia, D., Shepilov, Y., & Tsarev, A. (2013). Multi-agent system "Smart Factory" for real-time workshop management in aircraft jet engines production. *Proceedings of the 11th IFAC workshop on intelligent manufacturing systems (IMS'13)* (pp. 204–209). .

Spector, P. E. (1997). *Job satisfaction: Application, assessment, causes, and consequences.* London: Sage, London.

Tang, A., Owen, C., Biocca, F., & Mou, W. (2003). Comparative effectiveness of augmented reality in object assembly. *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 73–80). ACM.

Tisch, M., Hertle, C., Abele, E., Metternich, J., & Tenberg, R. (2016). Learning factory design: A competency-oriented approach integrating three design levels. *International Journal of Computer Integrated Manufacturing, 29*(12), 1355–1375.

Tisch, M., Hertle, C., Cachay, J., Abele, E., Metternich, J., & Tenberg, R. (2013). A systematic approach on developing action-oriented, competency-based learning factories. *Procedia CIRP, 7*, 580–585.

Turner, C. J., Hutabarat, W., Oyekan, J., & Tiwari, A. (2016). Discrete event simulation and virtual reality use in industry: New opportunities and future trends. *IEEE Transactions on Human-Machine Systems, 46*(6), 882–894.

Zhou, B., Zhang, B., Liu, Y., & Xing, K. (2011). User model evolution algorithm: forgetting and reenergizing user preference. *2011 IEEE international conferences on internet of things, and cyber, physical and social computing* (pp. 444–447). IEEE.